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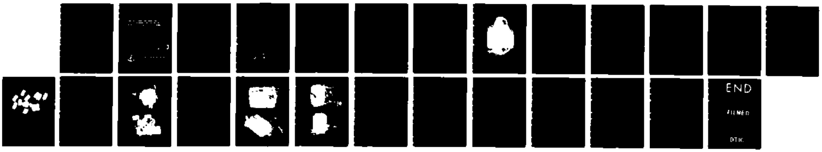

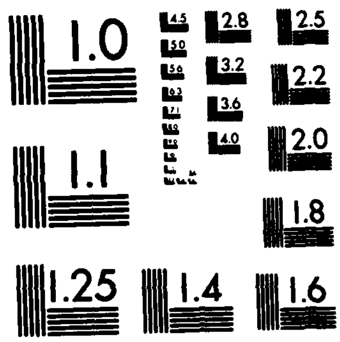

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CONSTANT CURRENT DISCHARGE TESTS OF A 12 "D" CELL IN SERIES Li/SO_2 BATTERY PACK UNDER COUNTER ARM DECOY REQUIREMENTS

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The results of discharging a candidate Li/SO_2 Counter Army Decoy battery at 21 amperes are reported and discussed. The candidate battery consisted of 12 "D" size Duracell LO-26SH.

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FOREWORD

This work was performed for and funded by the Counter Arm Decoy Program. The results and conclusions presented in this report concerning the behavior of Lithium/SO_2 batteries during high-rate constant current discharge should be of interest to those considering using lithium batteries as power sources and concerned with their performance and safety characteristics under high-rate discharge.

Approved by:

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CHAPTER 1

INTRODUCTION

This work was carried out in response to a request by Code F46 of the Naval Surface Weapons Center (NSWC) to evaluate a battery pack proposed for use in the Counter Arm Decoy System. The work was intended as a performance test to determine the battery voltage under forced discharge at 21 amperes. The Counter Arm Decoy System requires a battery which can provide this current at 28 volts $\pm$ 2 for 5 minutes over a temperature range from -40 to 71°C.

These battery packs were supplied by Code F46 to the Lithium Systems Safety Group of the Electrochemistry Branch (R33) for testing. The batteries were designated as Duracell product SRL-5744 and had been assembled in 1979 or 1980. They contained 12 Duracell LO-26SH lithium/sulfur dioxide cells wired in series and protected with a 30-ampere slow-blow fuse. The cells were manufactured on 4 April 1979. The battery is shown in Figure 1.

The LO-26SH is a "D" size cell which is marketed by Duracell for high rate pulse application in which it can deliver up to 30 amperes. The manufacturer's literature predicted that the cell should be able to deliver a constant current of 21 amperes to a 2.0 volt cut-off for about 0.15 hour (9 minutes) at 70°F (21°C). Although the LO-26SH is described as a high-rate cell, Duracell's data sheet does include the caution, "Discharge above 1.3 amperes, . . . should be intermittent, controlled or monitored to prevent overheating and possible venting or explosion." The battery packs tested here had an additional disclaimer, "Caution: This battery, when discharged at customer-required rates can be expected to vent SO_2, gas. Use extreme care to avoid breathing toxic fumes."

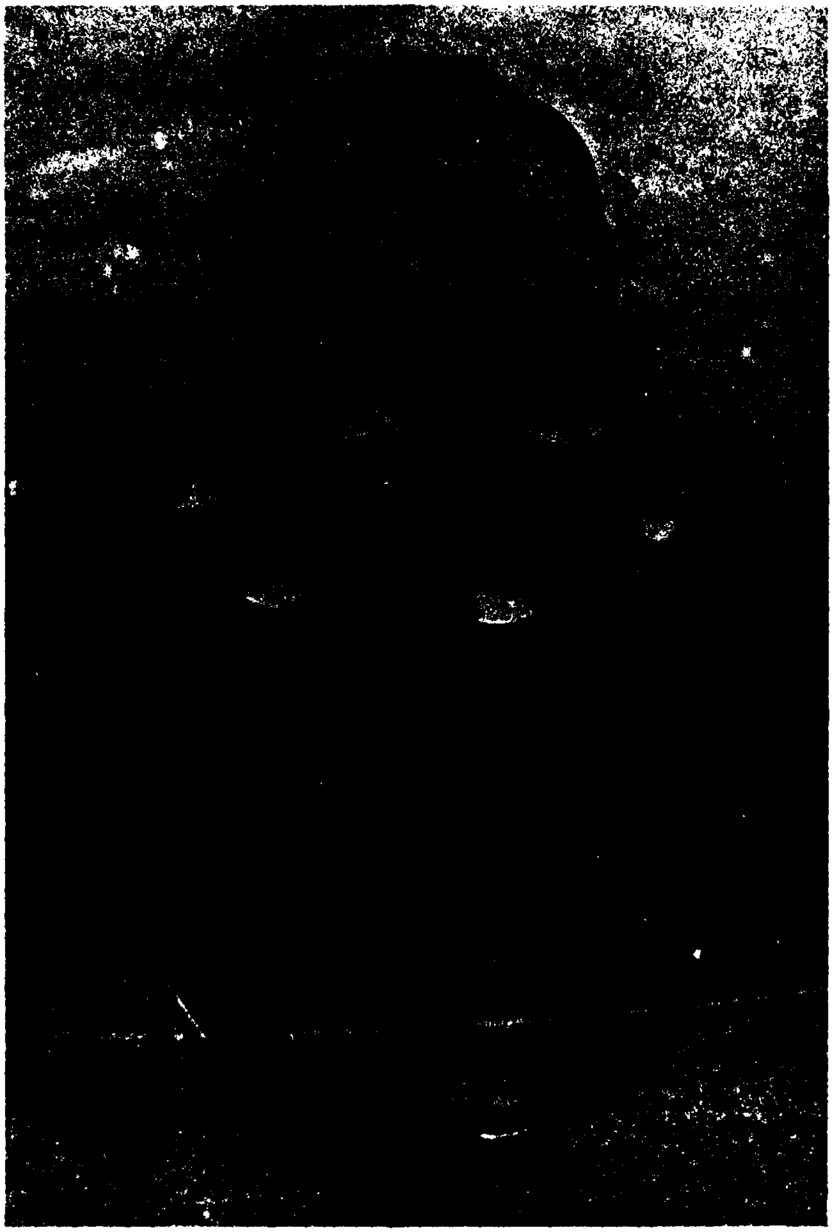

FIGURE 1. MALLORY 36V BATTERY WITH 12 "D" CELL (DURACELL L026SH) IN SERIES

CHAPTER 2

EXPERIMENTAL

Each battery was prepared for forced discharge as follows:

1. Six chromel alumel thermocouples were taped on the outside of the battery pack as depicted in Figure 2.

2. The battery pack was wrapped in 8 feet of 1/2-inch flexible electric heating tape* rated at 416 watts at 115 volts and connected to a variable transformer. This heat tape was installed as a safety precaution to provide a method to destroy the battery in the event that it survived the forced discharge test.

3. The battery pack was force discharged at a constant current of 21 amperes using the circuit shown in Figure 3. A Sorenson power supply was set at a constant current of 21 amperes and 36 volts. A Fluke 2240B Datalogger was used to monitor temperature, current, and voltage of the battery. The data were also recorded on a Columbia 300 tape recorder. The tests were monitored on video tape, and tapes are on file at NSWC.

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*Manufactured by Briskheat, Thermolyne Corporation, subsidiary of Syborn Corporation, 2555 Kerper Blvd., Dubuque, Iowa 52001.

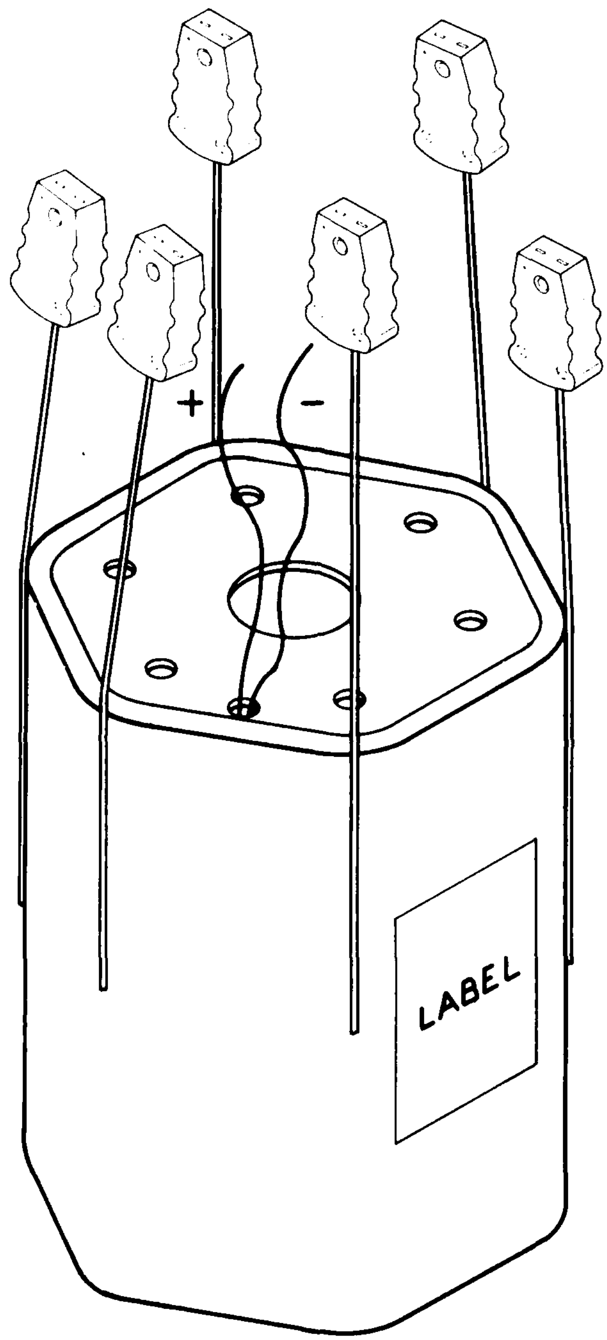

FIGURE 2. ARRANGEMENT OF K TYPE THERMOCOUPLES (6) ON THE BATTERY PACK

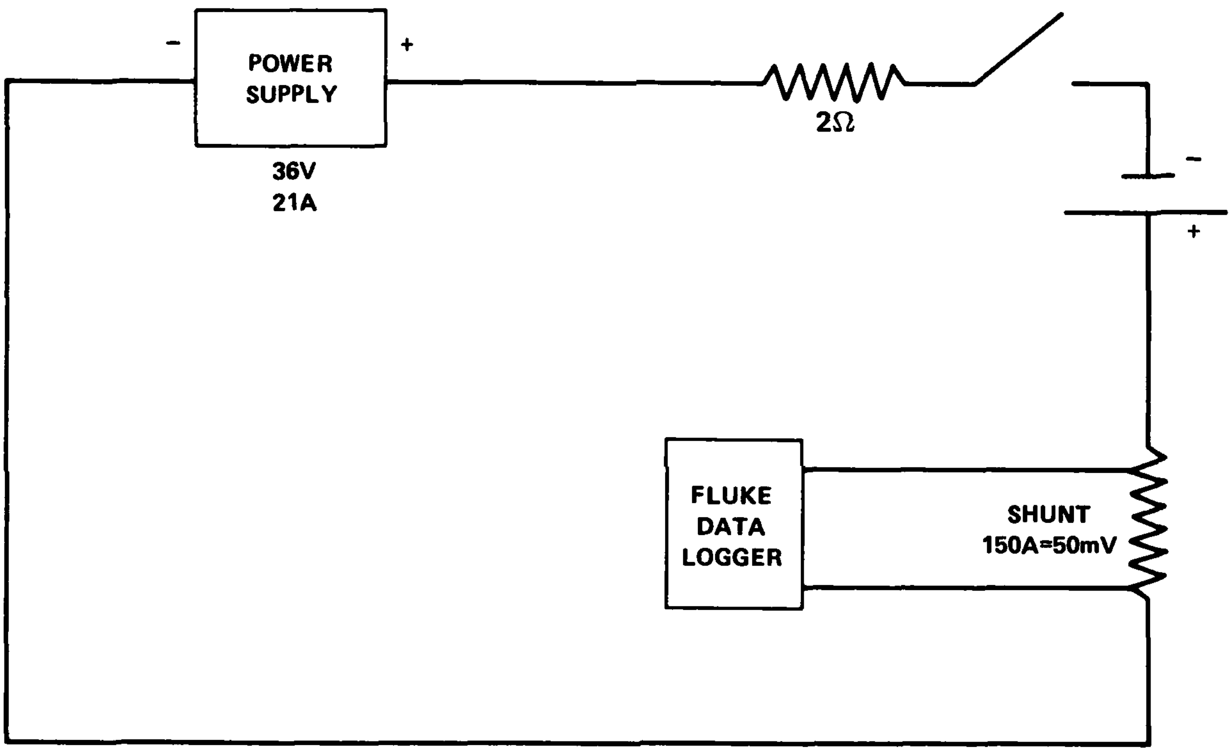

FIGURE 3. CIRCUIT FOR CONSTANT CURRENT FORCES DISCHARGE

CHAPTER 3

RESULTS

The first battery pack had an open circuit voltage of 36.10 volts. It was discharged at a fixed current of 21.5 amperes. With voltage limited to 36 volts, the current remained constant until the voltage went into reversal. When the switch was closed, the battery voltage went immediately to 23.22 volts. It partially recovered to a peak voltage of 26.09 volts, 3 minutes 4 seconds into the test. It then dropped off slowly until at 7 minutes into the test, it dropped off more quickly and went into voltage reversal (see Figure 4). Approximately 8 minutes into the test, an explosion occurred on one side of the pack, resulting in flames shooting out of the battery. Failures (presumably at the cell level) occurred at 8 minutes 20 seconds, 9 minutes 8 seconds, 9 minutes 29 seconds, 9 minutes 37 seconds, and 9 minutes 52 seconds into the test. The failures were accompanied by a "shooting" of flames and scattering of burning lithium. Nine minutes 37 seconds into the test, the battery was engulfed in flames. Ten minutes 11 seconds into the test a large explosion occurred scattering the cells over a radius of greater than 8 feet. The temperature history of the thermocouple reaching the highest temperature is shown in Figure 1. The remains were recovered and photographed. Nine cells appeared as would be expected with the vents open. Two were empty with the ends blown off. One of these two was also flattened. One cell blew out the side (see Figure 5).

The second battery had an open circuit voltage of 36.08 volts and was discharged at 21 amperes. The power supply in the circuit was limited to 36 volts. The current remained constant at 21 amperes ($\pm$ 0.05A) until the battery went into reversal. When the discharge began, the voltage immediately dropped to 24.14 volts. It partially recovered, reaching a maximum of 26.44 volts at 3 minutes 8 seconds. The voltage then dropped slowly for 4 minutes then it began to drop quickly. At 8 minutes 46 seconds the battery went into voltage reversal. At 8 minutes 49 seconds into the test, a "pop" occurred, accompanied by smoke. Seven seconds later flames began at the bottom and top of the battery. At 9 minutes 3 seconds into the test, an explosion knocked the battery over onto its side. "Pops" occurred at 9 minutes 9 seconds and 9 minutes 17 seconds into the test. At 9 minutes 45 seconds, 10 minutes 6 seconds, and 10 minutes 55 seconds into the tests, failures occurred resulting in "torch-like" flames. The temperature history of the hottest thermocouple as well as the battery voltage is shown in Figure 6. The vent and flame response described here is similar to results which have been observed many times during similar tests. The battery pack was somewhat intact after the test; although it fell apart after the heat tape was removed. Figures 7 and 8 show the battery before and after the heat tape was removed.

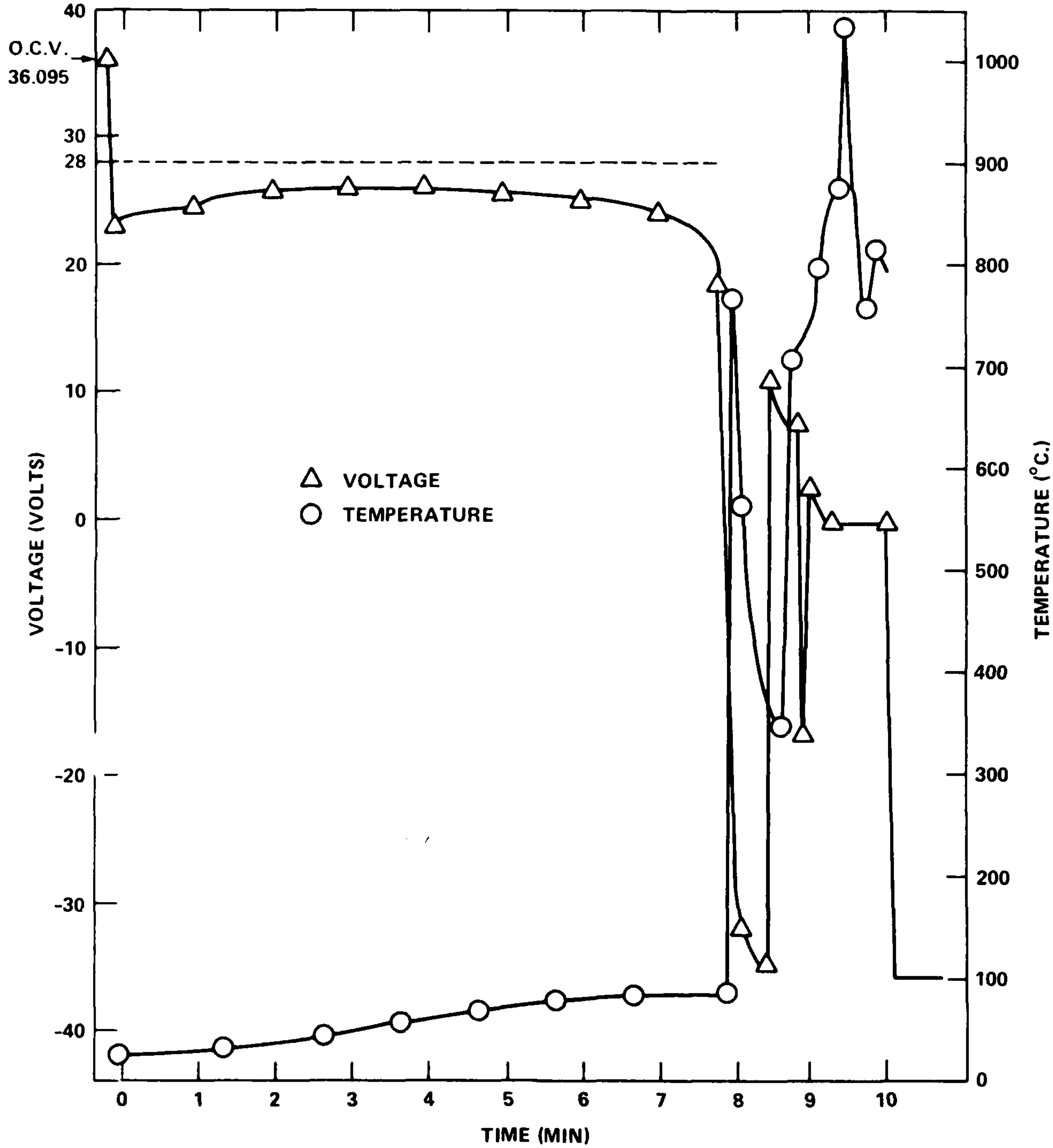

FIGURE 4. LITHIUM/SO_2 BATTERY (36 V; 12 D CELLS) CONSTANT CURRENT DISCHARGE (21 AMPS)

FIGURE 5. BATTERY PACK #1 AFTER CONSTANT CURRENT DISCHARGE

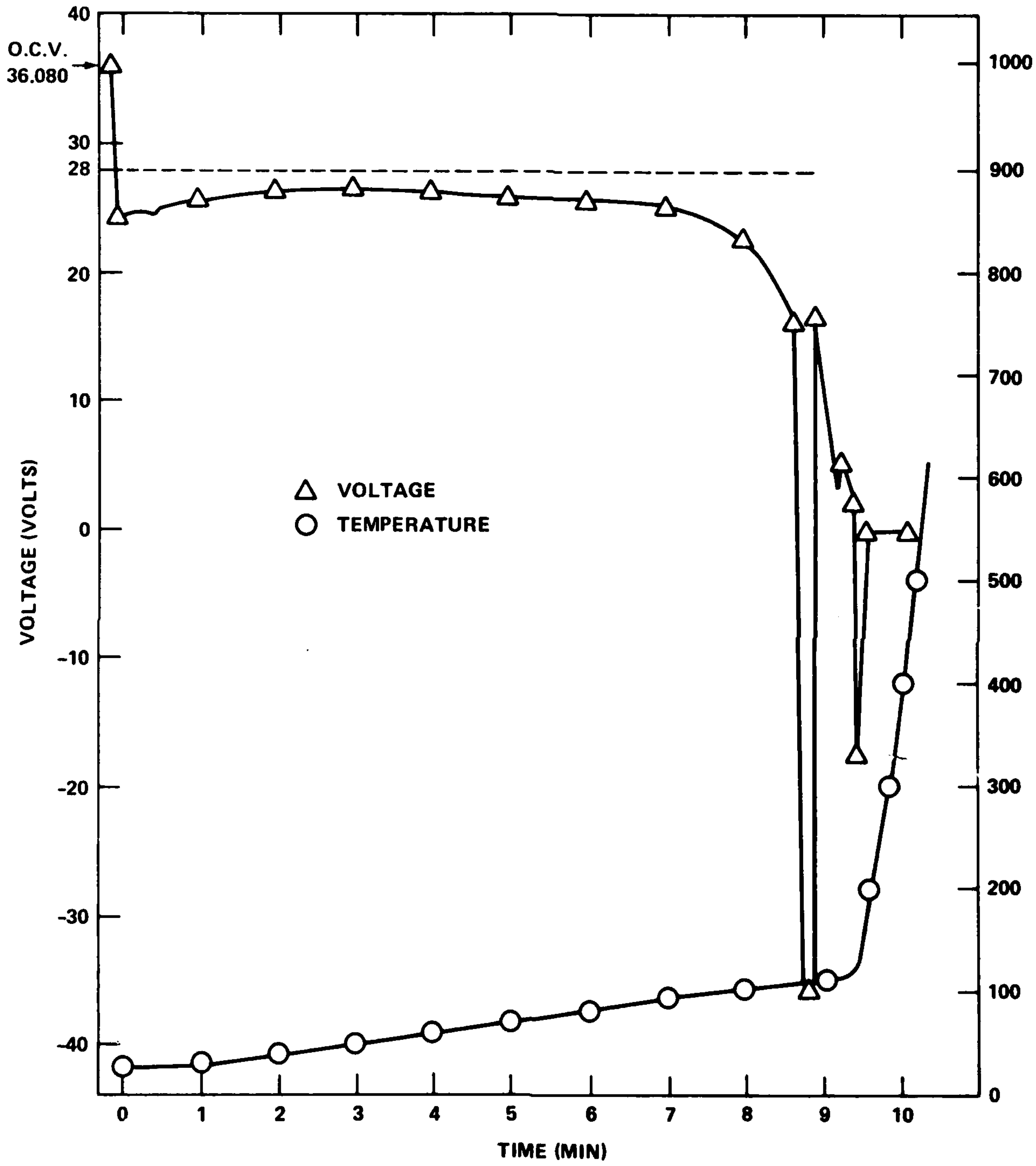

FIGURE 6. LITHIUM/SO_2 BATTERY (36 V; 12 D CELLS) CONSTANT CURRENT DISCHARGE (21 AMPS)

FIGURE 7. BATTERY PACK #2 AFTER CONSTANT CURRENT DISCHARGE (WITH HEAT TAPE INTACT)

FIGURE 8. BATTERY PACK #2 AFTER CONSTANT CURRENT DISCHARGE (WITH HEAT TAPE REMOVED)

The internal impedance of the third battery was too high to allow any appreciable current to be pushed through using the power supply after the switch was closed. The battery voltage dropped quickly to 24 volts, and then to 0. A short time after the start of the test (approximately 3 minutes), a local cell failure occurred with venting and flame. Flames lasted approximately 25 seconds and smoke about 1-1/2 minutes after the failure. No further events were observed for 8 minutes. The pack was then destroyed through incineration using heat tape with predictable results: venting and flame. Figure 9 shows the pack after incineration. The local failure can be seen as a hole burned through the heat tape. Figure 10 shows the pack with the heat tape removed.

The fourth battery pack was found to be defective. Using a multimeter, the pack had an internal impedance of greater than 100 ohms. The 21 ampere current necessary could not be run through the battery using the power supply. The battery was placed directly across the 2-ohm load. The voltage dropped immediately to 0 volt indicating at least one bad cell in the battery. The battery was incinerated using heat tape. The incineration produced predictable results with smoke, flames, an occasional "pop" and Li scattering. Figures 11 and 12 show the pack before and after the heat tape was removed.

The fifth battery pack supplied by F46 had an internal impedance of 21 ohms measured using a multimeter. It appeared as though it had been used before. It was not tested.

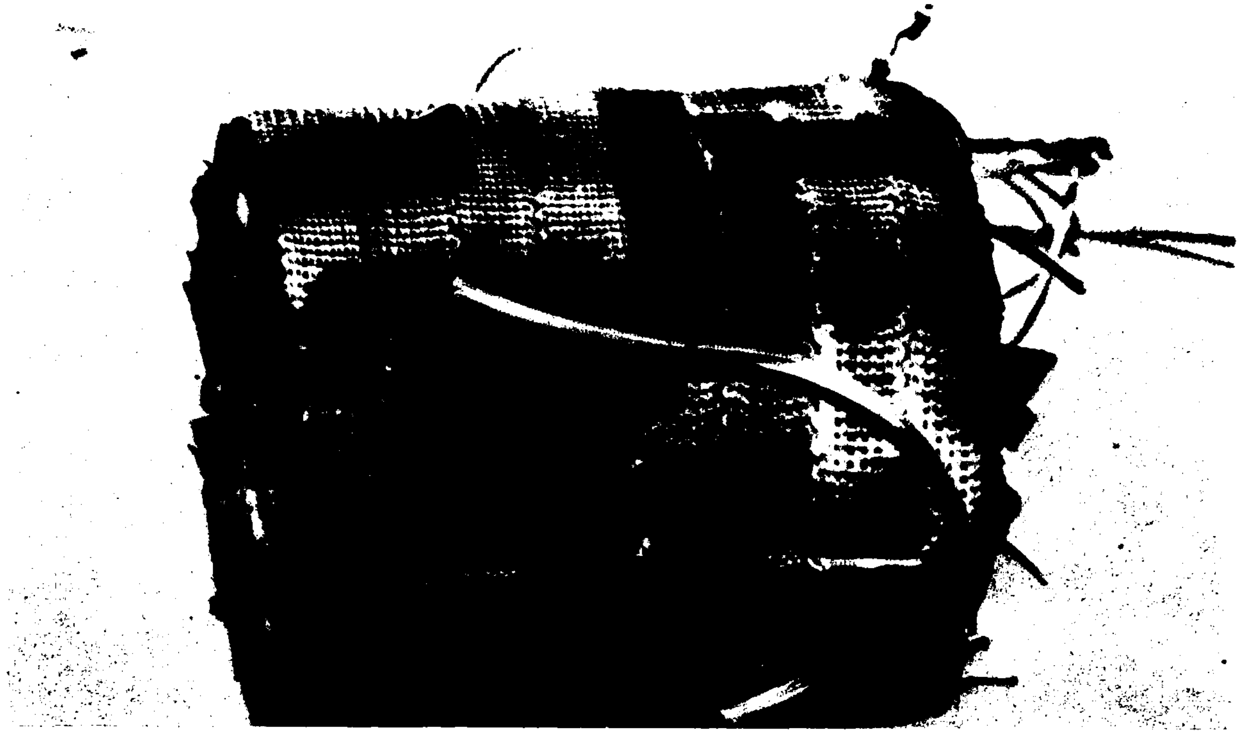

FIGURE 9. BATTERY PACK #3 AFTER DISCHARGE AND INCINERATION (WITH HEAT TAPE INTACT)

FIGURE 10. BATTERY PACK #3 AFTER DISCHARGE AND INCINERATION (WITH HEAT TAPE REMOVED)

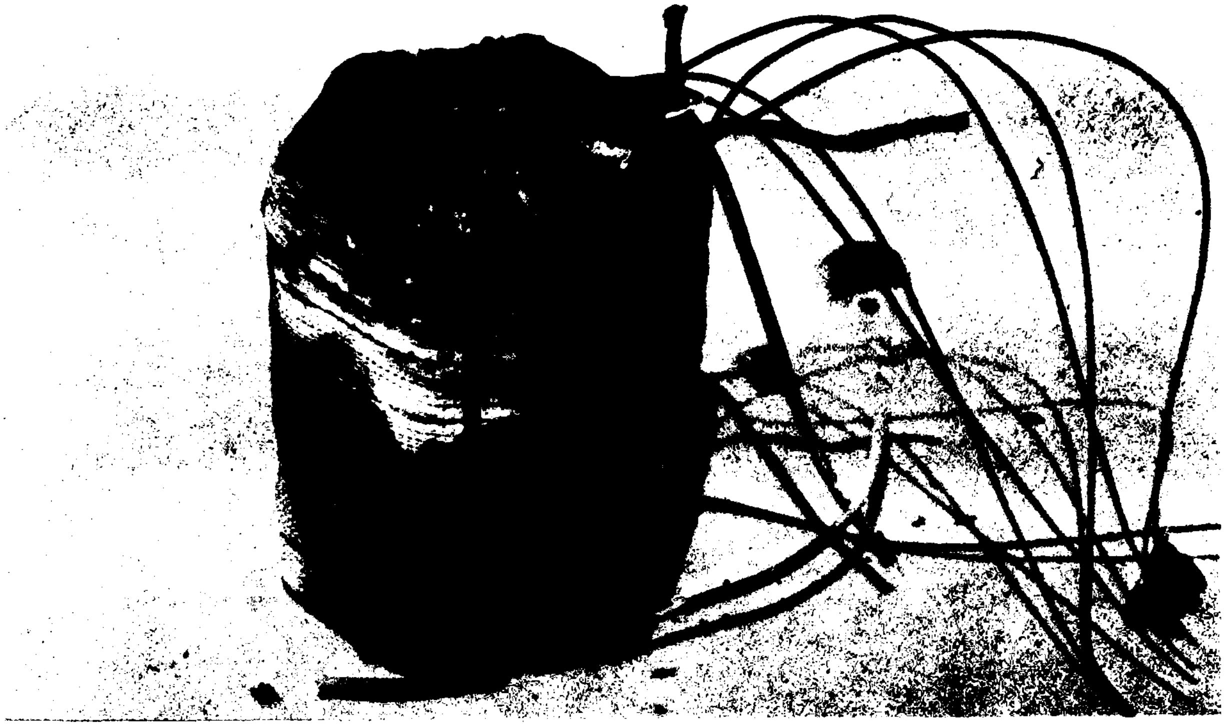

FIGURE 11. BATTERY PACK #4 AFTER INCINERATION (WITH HEAT TAPE INTACT)

FIGURE 12. BATTERY PACK #4 AFTER INCINERATION (WITH HEAT TAPE REMOVED)

CHAPTER 4

CONCLUSIONS

+ or -

None of the battery packs tested met the performance criteria of 28 volts $\pm$ 2 for 5 minutes under a 21-ampere discharge. Three of the five batteries supplied were defective and could not be tested. One of these three had a defective cell and the other two had a high internal impedance. At voltage reversal, the two batteries that were tested reacted violently. One vented violently sending cells in all directions. The other also vented violently with torch-like flames.

Capacities obtained under this test to a cut-off voltage of 2 volts were on the order of 2.80 and 3.03 amp hours. These capacities were in agreement with the discharge curves provided by the manufacturer for discharge at 70°F at 25 amperes. This recovered capacity is substantially less than the manufacturer published capacity at the C/2 rate (6.4 ampere hour at 3.2 amp discharge).

CHAPTER 5

RECOMMENDATIONS

1. The batteries provided for testing were unable to meet the performance requirements for voltage and current associated with the proposed use during a room temperature test. Batteries assembled from recently manufactured cells might give better performance under test; but on the basis of our experience, we would not expect to observe enough improvement to meet the specifications. Although no low temperature experiments were conducted, we would expect voltage/current performance to be an even greater problem at -40°C.

2. We know of no other lithium/active cells or batteries which are more likely to meet the voltage and current requirements within the limitations of size, weight, and cost.

3. We feel that other battery technologies, especially lithium thermal batteries, may be able to meet the operational requirements of the proposed use. A program to evaluate alternative batteries is now in progress under the direction of Mr. Alvin Rosen of the Electrochemistry Branch.

4. The fact that three batteries in our sample set of five units delivered little or no capacity under test is of concern. This behavior reflects serious problems of control during either manufacturing and/or storage and handling. If further units are tested, care should be taken to document this history. We have not attempted to determine whether the observed lack of capacity was the result of manufacturing flaws or of subsequent handling.

5. The variation of the modes of failure observed at voltage reversal and the severity of some of those failures are of concern to us. Significant safety hazards may be associated with the use of this battery at the proposed rate. Further extensive safety testing would be required before we could comment on the safety of the battery for evolution testing or Fleet use.

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